Manipulating Large-Area, Heavy Metal Ion Beams with a High-Current Electrostatic Plasma Lens

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***Abstract*—We describe some experimental investigations of the manipulation of high-current, large-area beams of heavy metal ions using a high-current electrostatic plasma lens. Beams of carbon, copper, zinc, and tantalum ions (separately) were formed by a repetitively pulsed vacuum arc ion source, with energy in the range about 10–140 keV, beam current up to 0.5 A, initial beam diameter 10 cm, and pulse length 250 ms. The plasma lens was of 10-cm internal diameter and 20-cm length and had nine electrostatic ring electrodes with potential applied to the central electrode of up to 7 kV, in the presence of a pulsed magnetic field of up to 800 Gauss. The current density profile of the focused beam was measured with a radially moveable, magnetically suppressed Faraday cup. The results show that the focal length of the lens and the profile of the transported beam can be controlled by variation of the lens magnetic field and electrode potential distribution. Under optimum operating conditions the ion beam current density at the focus was compressed by a factor of up to 30. We also carried out some preliminary observations of the effect of the plasma lens on the ion charge state distribution of the beam. Here we outline the principles underlying plasma lens operation and summarize the experimental observations we have made of the lens performance in this large-area, high-current regime.**

***Index Terms*—Intense ion beams, ion beams, ion focusing, plasma lens, plasma optics.**

I. Introduction

The MANIPULATION [bending, focusing, beam profile control, charge-to-mass (Q/A) analysis] of ion beams is well understood for the case of low current beams where space-charge neutralization of the beam is not required and is not a concern. But when the ion beam current is not low (more correctly the current density and mass and energy all play a role) and a high degree of space-charge neutralization by a background sea of cold electrons is required in order that the beam continue to propagate and not be lost to space charge blow-up, then there is a notable lack of techniques/tools for manipulating the beam in any way. High current ion beams cannot be focused by traditional electrostatic lenses or by magnetic quadrupoles in the "usual" way (usual referred to the well-developed technologies used for example in particle accelerator beam lines and in conventional ion implanters). If such manipulation is attempted for space-charge-dominated beams, space-charge neutralization is disrupted and the beam loss is severe and can indeed be complete. This circumstance has been a major impediment to the application of high current beams in a number of fields. Plasma ion sources and ion beam technologies have matured greatly in recent years, and wide-aperture, high-current, moderate-energy, heavy ion beams can now be made relatively straightforwardly, but their use has been limited by the inability to control or focus them. There is thus a need for alternatives to traditional beam-focusing tools for the case of high-current beams, particularly for moderate energy heavy ion beam manipulation, when space-charge forces are large. The electrostatic plasma lens is such an alternative. In this paper we outline the principles underlying plasma lens operation and describe the experimental observations we have made of the lens performance in this large-area, high-current regime.

II. Basic Relationships and Prior Work

The electrostatic plasma lens is an axially symmetric plasma-optics system with a set of cylindrical ring electrodes located within an externally driven magnetic field, with field lines connecting ring electrode pairs symmetrically about the lens mid-plane; see Fig. 1. (The electrostatic plasma lens is distinct from the magnetostatic plasma lens, where the beam focusing is provided by the azimuthal magnetic field of a plasma column with axial current.) The basic concept of this kind of lens was first described by Morozov and coworkers [1], [2] and is based on the use of magnetically insulated cold electrons (i.e., transverse mobility $\ll$ parallel mobility) to provide space-charge neutralization of the focused ion beam and maintain the magnetic field lines as equipotentials ("equipotentialization"). This is a generalization of the ideas of Gabor for employing magnetized electron clouds for ion beam focusing [3]. Electrons within the lens volume, formed for example by secondary emission following collision of beam ions with lens electrodes, are able to stream freely along the field lines, thereby tying the potential to that of the electrostatic ring electrode to which the field line is attached. A steady state is rapidly reached on the time-scale of the electron flow along field lines and preserved because of the closed azimuthal drift of electrons in the $\mathbf{E} \times \mathbf{B}$ field of the lens. The condition of equipotential field lines (of length $l \gg R$, the lens radius, passing through the axial region of the system and crossing the grounded, outermost electrodes) follows from a model in which the lens volume is uniformly filled with cold background electrons of density n_e and energetic beam ions of

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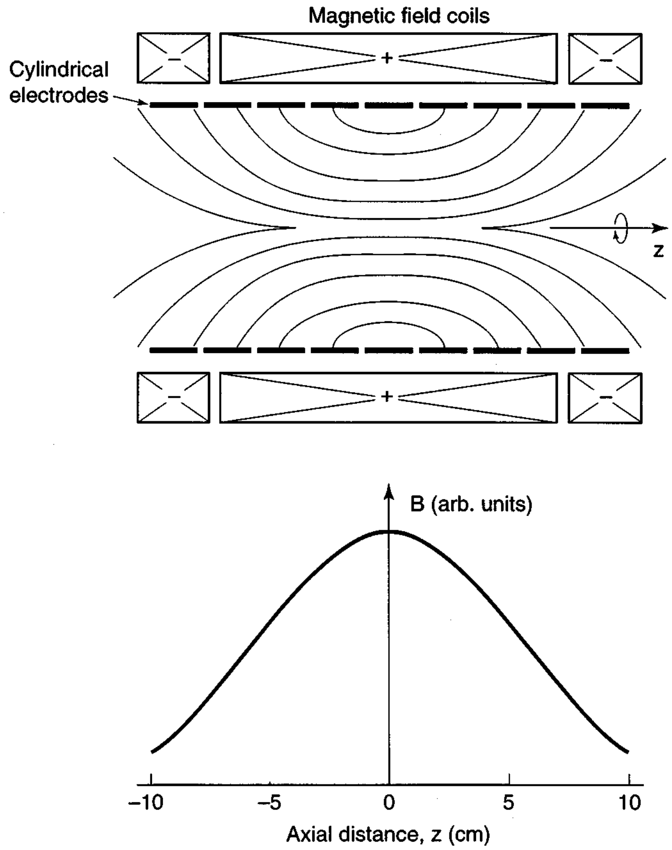


Fig. 1. Simplified schematic of the electrostatic plasma lens, showing the magnetic field coil and the nine cylindrical electrodes and the on-axis magnetic field shape $B_z(0,\ z)$. (The z scale refers to the lens used in the work described here).

density $n_b = I_b/eQv_b\pi R^2$, where I_b is the ion beam current, e the electronic charge, Q the ion charge state, v_b the beam ion velocity, and R the beam radius. This condition can be given as [4], [5]

$$n_e - \frac{I_b}{eQv_b\pi R^2} = \pm\frac{4\varepsilon_o\varphi_L}{eR^2} \tag{1}$$

where

- n_e electron density;
- e electronic charge;
- ε_o permittivity of free space;
- φ_L maximum electric potential on the ring electrodes;

the plus sign corresponds to beam focusing and the minus sign to beam defocussing. (Note that φ_L used here corresponds to U_L used later in describing the experimental results.) We take Q to be the mean ion charge state, for simplicity. However, as for all purely electrostatic charged-particle optical systems, the focussing characteristics of the electrostatic plasma lens are charge-state-independent, noting that the function of the lens magnetic field is to tie electrons to field lines and neglecting for now the small azimuthal $\mathbf{v}_{\text{ion}} \times \mathbf{B}_{\text{lens}}$ forces. (See later, however, our discussion about momentum aberrations.) In order for equipotential field lines to be generated, an electron density is needed that is sufficient to compensate for both the space charge due to the beam and the space charge due to the vacuum electric potential within the lens volume. It can be seen from (1) that beam focusing can be obtained for low beam current density—this is the Gabor lens. In this case the electrons are used only for compensation and transformation of the external vacuum electric field in order to make the electric field lines transverse to the magnetic field lines.

For a high current beam when, if unneutralized, the beam could blow up under its own space-charge forces, and neutralization can be provided by electrons of sufficient density held within the beam by its space charge. Lens operation in this regime occurs when the beam potential parameter $I_b/4\pi\varepsilon_0 v_b$ exceeds significantly the maximum externally applied lens voltage, $I_b/4\pi\varepsilon_0 v_b \gg \varphi_L$. Operation of the high-current plasma lens in this regime has been reported by us previously [4], [5]. In the high beam current regime, a quasineutral plasma is formed in the lens volume consisting of cold magnetized electrons drifting along the magnetic surfaces and fast beam ions that are affected to first approximation only by the radial electrostatic field of the lens. Note that the equipotentialization condition follows from the steady-state hydrodynamic equation of motion of cold electrons, which in this case is [2]

$$\mathbf{E} = -(\mathbf{v_d} \times \mathbf{B}) \tag{2}$$

where $\mathbf{v_d}$ is the velocity of the cold electrons, and $\mathbf{B}$ is the magnetic field within the lens volume. The macroscopic electrostatic field $\mathbf{E}$ is obtained only in the presence of closed electron drift and an "insulating" magnetic field. Then the electric field is perpendicular to the magnetic field, and the field lines are equipotentials. It follows that the self-consistent potential distribution in the lens volume depends on the magnetic field as

$$\Phi = k\Psi(r,\ z) \tag{3}$$

where k is a proportionality coefficient determined by the boundary conditions. Here the magnetic flow function Ψ is related to the magnetic field by

$$B_r = -\frac{l}{r}\frac{\partial\Psi}{\partial z}, \qquad B_z = \frac{l}{r}\frac{\partial\Psi}{\partial r} \tag{4}$$

and the lines $\Psi(r,\ z) =$ constant are magnetic field lines. It is also necessary that the magnetic field configuration should eliminate spherical aberrations and transfer ground potential (the potential of the outermost lens electrodes) to the beam axis at the midplane. We note parenthetically that by the term spherical aberrations we follow conventional usage and that of Morozov [1], [2], and refer to the case when the radial electric field $E_r(r)$ has a variation other than linear; when $E_r(r) \sim r$, there are no spherical aberrations, and a zero-divergence, mono-energetic, ion beam can be brought to a perfect focus.

The focal length of this kind of electrostatic plasma lens is given by [2]

$$F = \frac{\theta\varphi_b R}{2\varphi_L} \tag{5}$$

where φ_b is the ion beam accelerating potential (i.e., φ_b is the ion source extractor voltage and the energy of the beam ions is given by $E_b = eQ\varphi_b$) and θ is a geometric parameter that depends on the ratio of lens radius R to lens length L and the magnetic field configuration. The optimal configuration of magnetic field occurs [6] for $\theta = (\pi R/L)I_l(l)$, where I_l is the modified Bessel function, and for the optimal configuration $\theta \approx 1$. Importantly, note that the focal length of the plasma lens does not depend on the ion charge-to-mass ratio; this is a consequence of the purely electrostatic optical system, as previously noted.

Electrostatic plasma lenses have been investigated for half a century. This background work is characterized by a steady increase in the ion beam current I_b and the beam potential parameter $I_b/4\pi\varepsilon_0 v_b$. The current status of experimental investigation of the electrostatic plasma lens has been summarized in references [4]–[8]. Repetitively pulsed beams of hydrogen ions with current up to 2 A and energy up to 25 keV were used, entering the high-current regime for which $I_b/4\pi\varepsilon_0 v_b > \varphi_L$. In prior work [7] we have reported on the static and dynamic characteristics of the high-current plasma lens with quasineutral plasma created by fast beam ions and secondary emission electrons. Some features of the focusing of wide-aperture, low-divergence beams of hydrogen ions were investigated. In these experiments good agreement was obtained with theory. It was theoretically predicted that a lens without spherical aberrations can be obtained by creation of the optimum magnetic field configuration and selection of the optimum distribution of externally applied ring-electrode potentials, and optimization of the number of ring electrodes and their dimensions. These experiments confirmed good operation of the electrostatic plasma lens and a high degree of predictability, but the maximum beam compression (ratio of focused to unfocused ion beam current density at the focal spot) was limited to disappointingly low values of 2 to 5. It became clear [6] that this limitation in beam compression was connected primarily to nonremovable momentum aberrations due to the azimuthal rotation of beam particles in the lens magnetic field. These aberrations depend on the ion charge-to-mass ratio through the beam velocity v_b and restrict the minimum radius of the beam at the focus to

$$R_{\min} = R_0 \frac{v_b BL}{\varphi_b \pi c} \tag{6}$$

where R_0 is the initial radius of the beam. Beams of protons with energy 10–25 keV and low-energy singly charged copper ions with energy 200–400 eV both come to a focus of radius $R_{\min} \sim 1$ cm, for typical lens parameters ($B \sim 0.1T$). In experiments [6] with multiply charged ion beams (Cu, Zn, Mo) formed by a vacuum arc ion source and with energies 100–400 eV it was demonstrated that the lens gave rise to charge-state separation of particles at the focus. For higher energy heavy ions, the effect of momentum aberrations is much reduced, and for 20–30 keV copper ions a focal spot size of $R_{\min} \sim 1$ mm can be produced.

In work preliminary to that described here, an experiment was performed at Kiev to model the conditions needed for carrying out high-dose metal ion implantation at moderate energies (say, 10–100 keV). Using a vacuum arc ion source, we formed repetitively pulsed, wide-aperture copper ion beams with energies 10–25 keV, current up to 800 mA, pulse length about 100 μs, and initial beam diameter 5.6 cm. The value of the beam potential parameter $I_b/4\pi\varepsilon_0 v_b$ for such a beam is comparable to its energy. A beam with these parameters can exist only in the fully compensated state (i.e., fully space-charge neutralized), with the cold electron background produced for example by secondary emission from the surrounding electrodes. Our experiments showed [9], [10] that this leads to a significant increase in the electron current flow from the background plasma to the lens electrodes, by about an order of magnitude compared to the case of a hydrogen ion beam. Operation of the lens with a resistive voltage divider to supply the ring electrode voltages is then not reasonably possible because of the high currents involved, and we used instead an RC-divider which was able to hold the electrode voltages constant throughout the beam pulse. For optimal conditions of minimized spherical aberrations, we showed that the maximum current density of copper ion current onto a target at the focus is about 170 mA/cm^2, a compression at the focus of a factor of 20. These preliminary experiments carried out at Kiev provided the background for the work described here carried out at Berkeley. Some early results of these experiments describing the optimum operating conditions have been briefly summarized previously [11]; here the work is reported in detail.

III. Experimental

The experiments were carried out using the Mevva-V ion source and test-stand described in detail elsewhere [12]. Beams of heavy metal ions including C, Cu, Zn, and Ta were formed, with beam extraction voltage up to 50 kV, beam current up to 500 mA, initial (extractor) diameter 10 cm, pulse duration 250 μs, and pulse repetition rate 2.5 pulses per second. Note that the ions produced by the vacuum arc ion source are in general multiply stripped, with a mean of the ion charge state distribution of 1.0 for C, 2.0 for Cu, 1.2 for Zn, and 2.9 for Ta [11]. Thus the mean energy of the extracted ion beam was up to 145 keV for Ta. The midplane of the plasma lens was located 34 cm from the ion source extractor. The diameter of the lens input aperture was 10 cm, the length of the lens was 20 cm, and the number of electrostatic ring electrodes was nine. The electrodes were fed through a 110-kΩ voltage divider by a low-impedance, stabilized power supply. The highest potential $U_L \leq +7$ kV was on the central lens electrode, and the remaining symmetrically disposed electrodes were connected in pairs to the appropriate voltage divider points. The power supply provided fixed voltages to the lens electrodes during transport of the beam through the lens.

The required magnetic field configuration within the lens volume was determined by computer simulation and by an experimental simulation with iron filings and was confirmed by magnetic probe measurements inside the lens. The pulsed magnetic field was established by a number of coils surrounding the lens fed by a simple triggered capacitor bank and was of magnitude up to 800 G and pulse length 500 μs. The magnetic field shape on axis, $B(0, z)$, for the optimum configuration is shown in Fig. 1. The base pressure in the vacuum chamber was about 5×10^{-6} Torr. A secondary plasma was formed within the lens volume by the ion beam itself by secondary electron emission from the lens electrodes. Note that ionization of the background gas by the beam is not a significant effect at our operating pressure and beam pulse length.

The beam current density was measured by a radially movable, magnetically suppressed Faraday cup located 34 cm down-

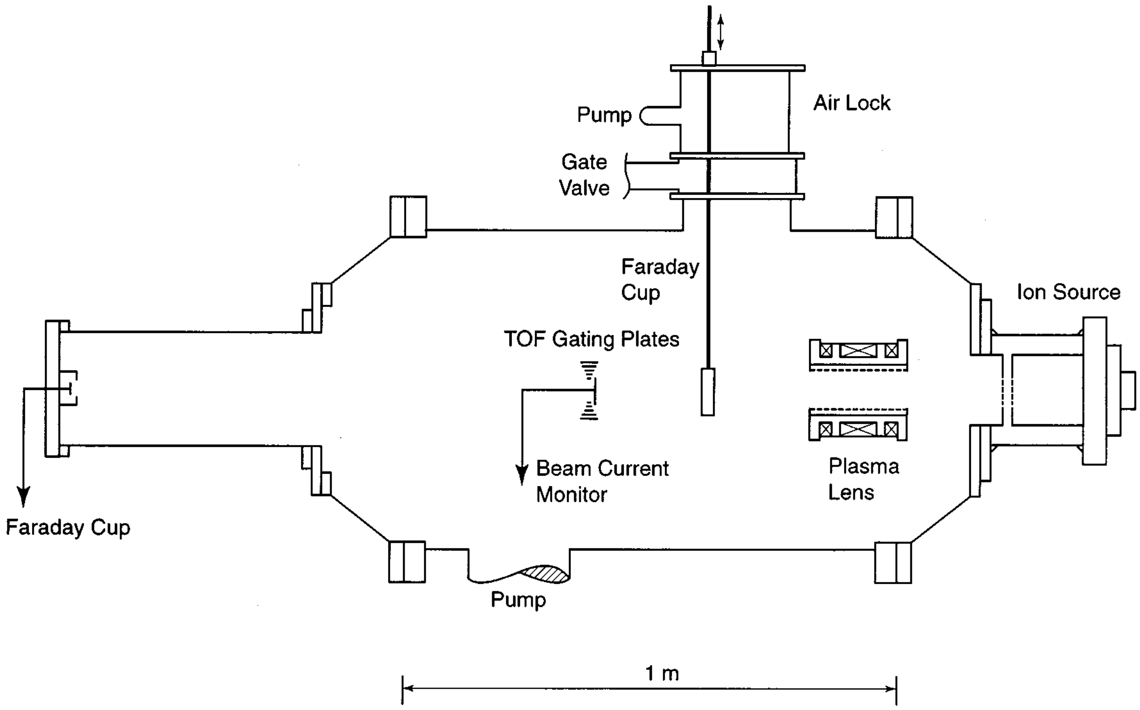


Fig. 2. Simplified schematic of the experimental configuration.

stream from the lens midplane. The entrance aperture of the Faraday cup was a 1-cm diameter for most of the work reported here, but we reduced this to 3 mm for some measurements so as to obtain greater spatial (radial) resolution. The total ion beam current was measured by scanning the Faraday cup radially and integrating the radial beam profile. We also monitored the total current by a simple collector plate without suppression of secondary electrons. A time-of-flight ion charge state analysis system [13] was used to monitor the ion charge state spectrum of the beam transported through the lens. A schematic of the experimental configuration is shown in Fig. 2.

IV. Results

Experimental measurements have shown, in prior work as well as here, that the plasma lens focusing characteristics depend strongly on the externally applied potential distribution along the electrostatic ring electrodes. Variation of the electrode potential distribution can change the lens operating regime from focusing to defocussing. In the work described here we carried out experiments for several different axial electrode potential distributions. The results obtained for the case of a tantalum ion beam are described in the following.

A. Lens Potential Distribution

1) Very Short Potential Distribution: The very short potential distribution refers to the case when the central lens ring electrode alone has a positive potential, and all the other eight electrodes are grounded. The ion current density j_i of the tantalum ion beam at the Faraday cup location is shown as a function of the accelerating voltage $U_{\rm acc}$ for two different electrode voltages U_L in Fig. 3. The data show that the beam is focused to a maximum current density at optimum values of the accelerating voltage and lens voltage. The compression of the ion beam at the focus increases with beam energy and is as high as a factor of 7 for $U_{\rm acc} = 21$ kV and a lens electrode voltage $U_L = 6.6$ kV.

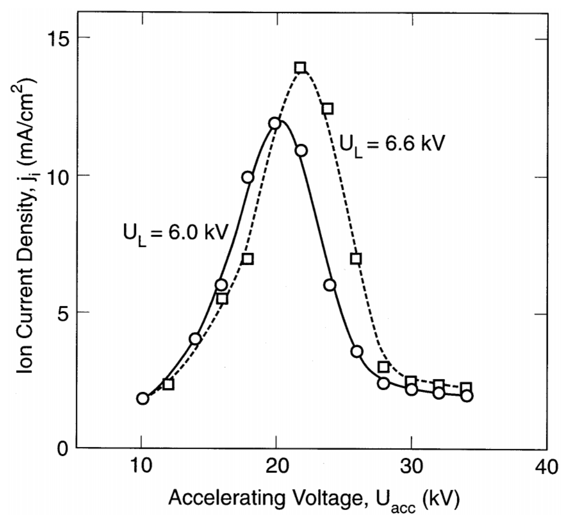


Fig. 3. Tantalum ion beam current density j_i at the Faraday cup as a function of beam accelerating voltage $U_{\rm acc}$. Very short potential distribution $B = 400$ G.

2) Short Potential Distribution: The short potential distribution refers to the case when the three central lens ring electrodes have a positive potential and the other six electrodes are grounded. The ion current density j_i of the tantalum ion beam at the Faraday cup is shown as a function of lens central electrode voltage U_L and of the accelerating voltage $U_{\rm acc}$ in Fig. 4(a) and (b), respectively. The variations are similar to those described above, but now the maximum ion beam compression at the focus is greater, and can be as high as a factor of 13.

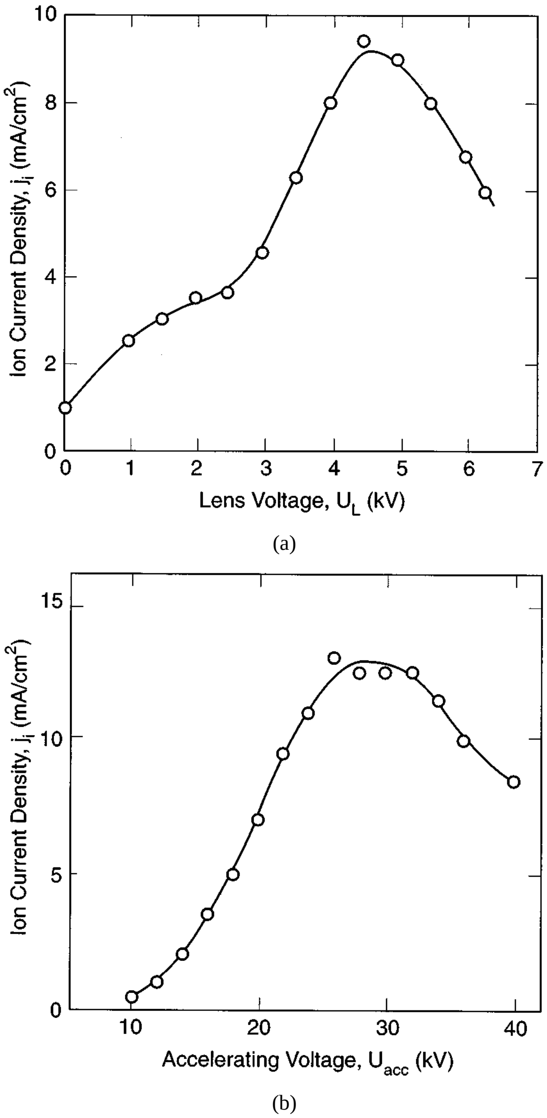


Fig. 4. Tantalum ion beam current density j_i at the Faraday cup for the short potential distribution: (a) as a function of lens central electrode voltage U_L; $U_{\rm acc} = 20$ kV, $B = 500$ G and (b) as a function of beam accelerating voltage $U_{\rm ac}$; $U_L = 6$ kV, $B = 500$ G.

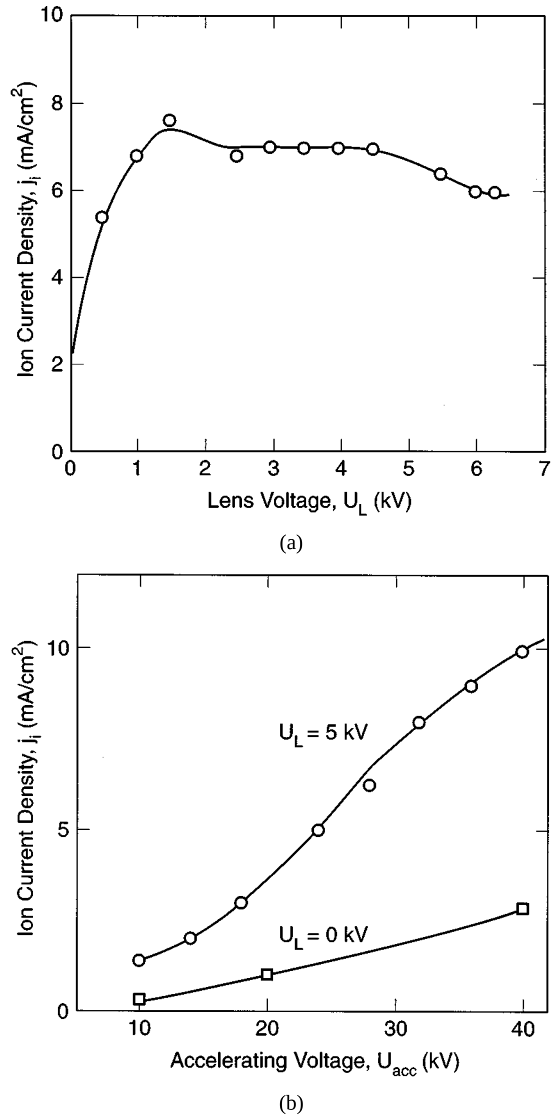


Fig. 5. Tantalum ion beam current density j_i at the Faraday cup for the long potential distribution: (a) as a function of lens central electrode voltage U_L; $U_{acc} = 20$ kV, $B = 800$ G and (b) as a function of beam accelerating voltage $U_{\rm acc}$, for lens-on ($U_L = 5$ kV) and lens-off ($U_L = 0$); $B = 800$ G.

3) Long Potential Distribution: For the case when the five central electrodes of the lens have the same positive potential U_L and the four outermost electrodes are grounded, the focusing characteristics of the lens cease to be resonant. The results shown in Fig. 5 illustrate this; one can see in Fig. 5(a) that the beam current density shows no characteristic maximum in its U_L variation, and in Fig. 5(b) that the current increases with beam energy by up to a factor of 5.

4) Very Long Potential Distribution: Finally, when all except the two outermost electrodes are held at a potential U_L, the focusing properties of the lens change dramatically. The lens starts to operate in a defocussing mode. The dependencies $j_i(U_L)$ for different values of $U_{\rm acc}$ are shown in Fig. 6. One can see that the lens causes a significant decrease of beam density at the collector, and the higher the beam energy the greater is this unexpected effect.

5) Optimal Potential Distribution: The effect of spherical aberrations within the lens volume is minimized for the case of the optimum distribution of electrode potentials. In this case $\Phi(R, z) \sim B_z(0, z)$ as shown in Fig. 1. For this condition, the dependencies $j_i(U_L, U_{\rm acc})$ have a distinctive sharply resonant character, see Fig. 7(a) and (b), and the maximum beam compression at the focus is a factor of 20–25. (The Faraday cup entrance aperture for these data was 1 cm; for a 3-mm aperture, the maximum observed compression was a factor of 30). The good beam focussing could be visually observed in the form of a bright spot of overall diameter 2–3 cm at the Faraday cup; it was not possible to distinguish, by eye, the intensity variation within this region. Oscillograms showing the ion beam current collected by the on-axis Faraday cup for the lens on, and with the optimal potential distribution, compared to the case with lens off, are shown in Fig. 8. Note that the pulse shape of the focused beam follows the initial beam pulse shape. That is, under these conditions the lens neither distorts the focused beam pulse-shape nor introduces any additional beam noise.

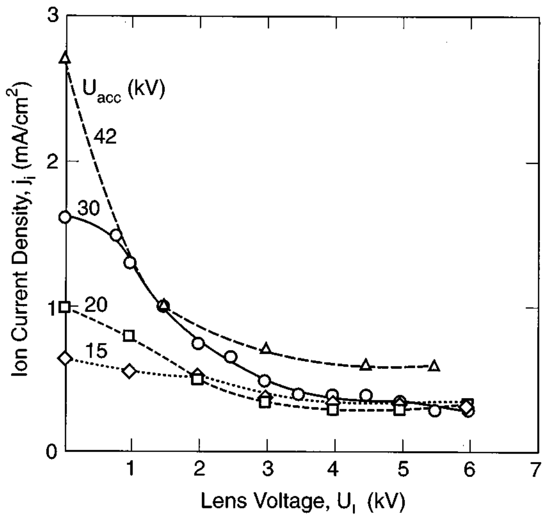
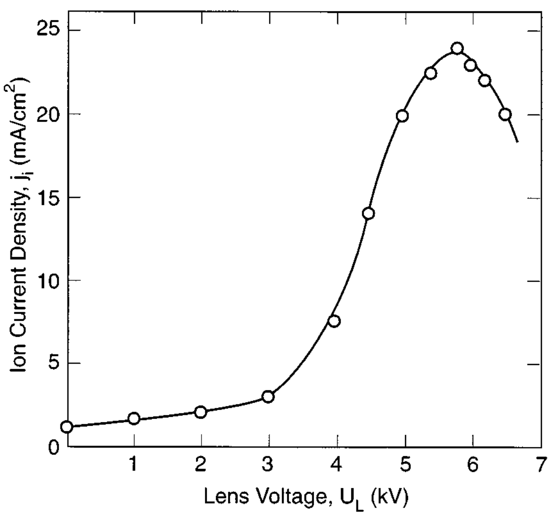
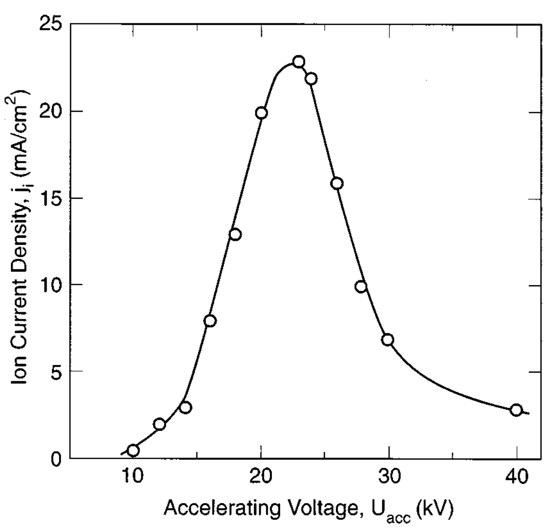


Fig. 6. Tantalum ion beam current density j_i at the Faraday cup as a of lens central electrode voltage U_L, for different values of beam accelerating voltage $U_{\rm acc}$. Very long potential distribution $B = 600$ G.



(a)



(b)

Fig. 7. Tantalum ion beam current density j_i at the Faraday cup for the optimum potential distribution: (a) as a function of lens central electrode voltage U_L; $U_{acc} = 22$ kV, $B = 800$ G and (b) as a function of beam accelerating voltage $U_{\rm acc}$; $U_L = 5.5$ kV, $B = 800$ G.

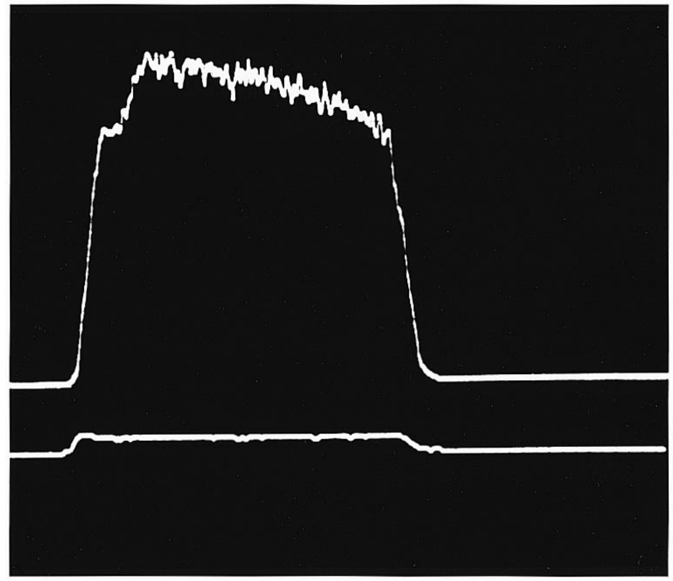


Fig. 8. Oscillograms of the beam current at the on-axis Faraday cup, for the case of maximum current compression and when the lens electrode potential distribution is optimum. Beam accelerating voltage $U_{\rm acc} = 22$ kV. Vertical scale 5 mA/cm for both traces; horizontal scale 50 μs/cm sweep speed; Upper trace: lens on; $U_L = 5.5$ kV, $B = 800$ G and Lower trace: lens off.

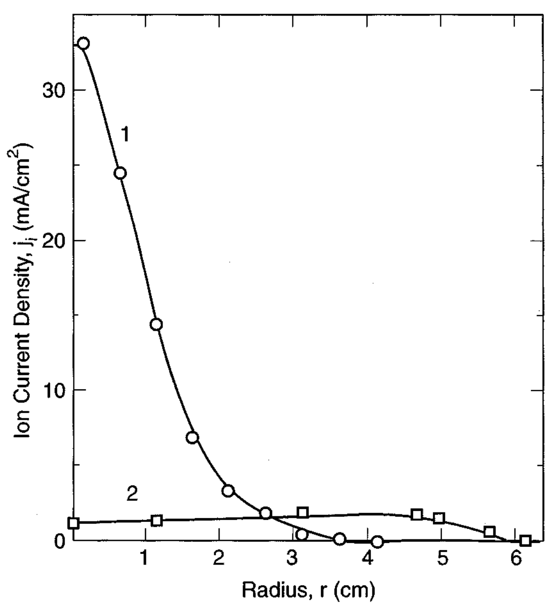


Fig. 9. Radial beam profile at the Faraday cup location, for the optimum electrode potential distribution. Faraday cup entrance aperture was a 3-mm diameter. Beam accelerating voltage was $U_{\rm acc} = 22$ kV. Curve 1: $U_L = 6$ kV; $B = 800$ G kV. Curve 2: Lens off, $U_L = 0$.

B. Radial Ion Current Density Distribution

The radial profile of the focused ion beam depends on the lens electrode potential distribution as shown in Fig. 9. One can see that the high optical strength of the lens is most distinct for the optimal potential distribution, when the role of spherical aberrations is minimal and the beam profile is bell-shaped. These data were obtained using a 3-mm Faraday cup entrance aperture. The radial profile of the focused ion beam could be varied over a broad range; some measured profiles are shown in Fig. 10 for the very short potential distribution. Note that by changing

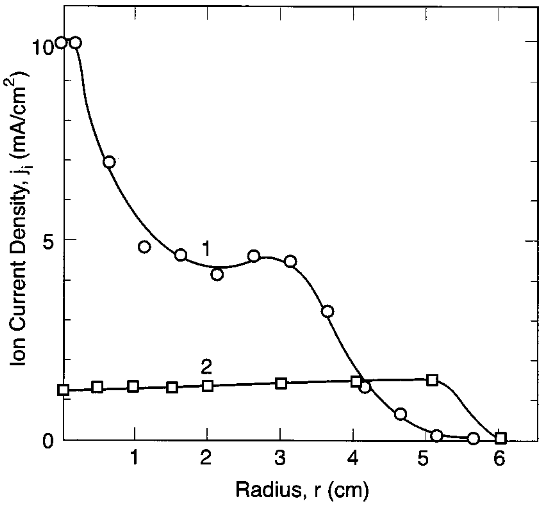


Fig. 10. Radial beam profile at the Faraday cup location. Beam accelerating voltage was $U_{\rm acc} = 26$ kV. Curve 1: very short electrode potential distribution $U_L = 6$ kV; $B = 800$ G and Curve 2: lens off, $U_L = 0$.

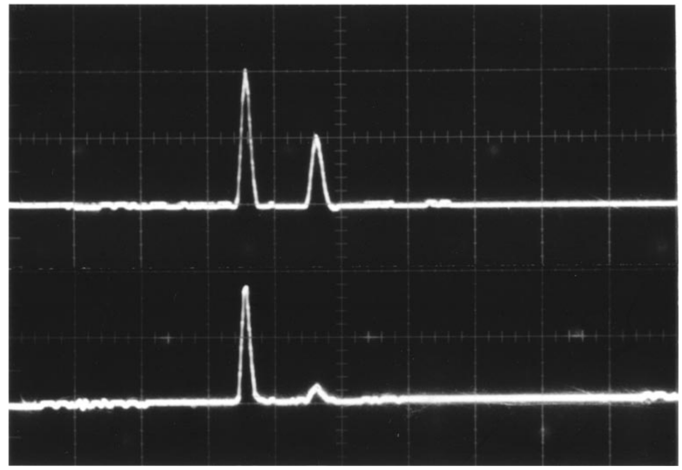


Fig. 11. Time-of-flight ion charge state spectrum showing the effect of the lens action on the on-axis charge state distribution of a zinc ion beam. Very long lens electrode potential distribution; beam accelerating voltage $U_{\rm acc} = 27$ kV. The peaks correspond to (right to left) Zn^{+} and Zn^{2+}. Upper trace: lens off; $U_L = 0$ kV; $B = 0$. Lower trace: lens on; $U_L = 4$ kV; $B = 800$ G.

the electrode potential distribution and magnetic field strength an approximately flat radial profile can be obtained.

Interestingly, the total beam current transported through the lens, $I = 2\pi \int j(r) r dr$, is greater for the focused (lens-on) beam than for the unfocused (lens-off) beam. Thus when the lens is off ($U_L = 0$ and $B_L = 0$) the integrated beam current at the Faraday cup $I_b(\text{lens off}) = 175$ mA (see Fig. 9, curve 2), while when the lens is on ($U_L = 6$ kV and $B_L = 800$ G) (curve 1), then $I_b(\text{lens on}) = 233$ mA, a factor of 1.33. This effect is yet more pronounced for the very short potential distribution, when the high electric field under the central electrode efficiently collects peripheral ions toward the axis. Then $I_b(\text{lens on})$ (Fig. 10, curve 1) is 255 mA for $I_b(\text{lens off}) = 154$ mA, a factor of 1.65. These observations imply, of course, not that beam is created by the lens action, but that beam which is lost to the lens wall (inner surface of the cylindrical lens structure) when the lens is off, is transported efficiently and with minimal loss when the lens is on. Note that this effect can explain the two-step $j(r)$ profile and the sharp maximum on axis because of strong spherical aberrations in this case.

C. Ion Charge State Distributions

To the extent that the plasma lens is purely electrostatic, its optics are charge-state-independent, as described above. However, inclusion of the azimuthal $\mathbf{v}_{\rm ion} \times \mathbf{B}_{\rm lens}$ force adds a small charge-state-sensitive term to the optics; these effects are referred to as momentum aberrations. For the case of an ion beam containing a distribution of ion charge states, this can lead to charge state separation of the beam at the focus. The radial profile of the focused ion beam can have a multi-stepped shape due to momentum aberrations, which is related to the fact that the minimum radius of the focused beam depends on the charge-to-mass ratio of the ions. However, the momentum aberration effects decrease with increasing ion mass and energy, and for the case of heavy ion focusing (Cu, Zn, Ta) with energy some tens of keV, charge state separation effects can be neglected.

We chose to employ the defocussing regime of lens operation for charge state analysis of the beam by the time-of-flight method [13]. In this case the beam radius increases with distance d from the midplane of the lens. It can be shown from geometric considerations that the beam radius R^* of a beam defocused by a thin lens is given by

$$R^* = R_0 \cdot \left(1 + \frac{d}{F}\right) \cdot \sqrt{1 + \left(\frac{R_{\min}}{R_0}\right)^2}. \qquad (7)$$

Here $R_{\min}/R_0$ is determined by (6) and thus depends on Q, and F is the focal length of the lens given by (5). The charge state separation properties of the lens become most evident for beams of elements with a high percentage of singly charged ions because of details of the time-of-flight method. As an example, oscillograms showing time-of-flight data (i.e., the charge state distributions) for zinc ions are shown in Fig. 11. These results show that the lens tends to reduce the singly charged ion component of the beam on axis, thus preferentially filling the periphery with ions of higher charge states. The effect is clear, if small.

V. Discussion

That the plasma lens has a defocussing mode of operation, accessed for the case of the very long potential distribution as described in the preceding, begs explanation. This behavior would seem to be in disagreement with the theory summarized above (and also with previous experimental results [9]). We explain this observation in the following way. In the present lens design, the outermost ring electrodes, which are grounded, are located further from the lens midplane than are the magnetic field coils. Consequently the magnetic field strength at the axial location of these electrodes is about the same as for their neighboring electrodes. Thus, secondary electrons, necessary for beam space charge compensation and for the formation of equipotential surfaces within the lens volume, come from the nearest electrodes at high positive potential. The beam within the lens is less space-charge- neutralized according to its own un-neutralized potential parameter $I_b/4\pi\varepsilon_0 v_b$; (see Fig. 6, showing that with increasing energy, the beam current increases faster than its velocity). The defocussing properties of the plasma lens for the very long potential distribution can be similarly explained. Note that the defocussing regime described here provides a demonstration of the ion charge state separation capability of the lens. The defocussing regime could find application as a tool for the formation of a more homogeneous or diffuse beam profile.

The experiments demonstrate the multifunctional possibilities of the electrostatic plasma lens operating with moderate-energy, high-current, heavy ion beams. The plasma lens may be used as a strong-focusing device for creation of a spot with high energy and mass concentration at the focus. For the optimal lens electrode potential distribution the maximum tantalum ion beam current density compression at the focus was a factor of 30.

Momentum aberrations manifest themselves for focused beam compressions greater than about 1000. Using some equations from [7] [$j_{\max} \le j_0 (R_o^2/F^2)(E_b/T_{io})$ because of the finite phase volume of the beam, where T_i is the temperature of ions in the source, E_b is the beam energy] and

$$j_{\max} \le j_0 \exp\left(\frac{R_o^2}{F^2}\frac{mv_b^2}{2eQ}\frac{4\pi\varepsilon_0}{\alpha I_b/v_b}\right) \tag{8}$$

due to incomplete compensation of the beam at the focus (α is the beam space charge compensation coefficient), one can show that for the experimental conditions ($U_{\rm acc} = 30$ kV, $U_L = 6$ kV, $R_0 = 5$ cm) both these parameters may be manifested for beam pinches more than 1000. Here we take $T_{i0} \le 4$ eV and potential break in the focused beam according to measurements from [8] is $\alpha I_b/4\pi\varepsilon_0 v_b \sim 100$–200 V. We conclude that the maximum beam compression achieved experimentally is restricted by nonremovable spherical aberrations, even for the optimal electrode potential distribution. Further theoretical and experimental work on the formation of optimal magnetic field configurations and lens electrode potential distributions could lead to more complete removal of spherical aberrations, and to lens compression factors yet an order of magnitude greater than those observed here.

VI. Conclusion

The experiments described here demonstrate the high efficiency of the electrostatic plasma lens for manipulating wide aperture, high-current, moderate energy, heavy ion beams. In the present work, a 10-cm diameter tantalum ion beam with 70-keV mean ion energy and 0.24 A current was focused to a focal spot for which the current compression factor was up to a factor of 30 for the optimum lens electrode potential distribution. The plasma lens provides a tool that could be of value for high dose ion implantation, for example. The removal of lens spherical aberrations could lead to the ability to focus high current beams by a compression of up to as much as a factor of 1000. Further effort on optimization of the magnetic field, for example by using permanent magnets rather than current-driven coils, is also needed. This could open up some novel areas for the practical application of high current ion beams.

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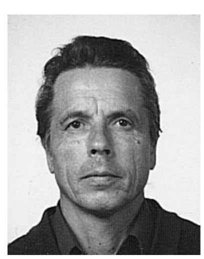

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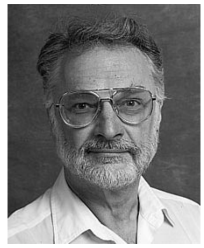

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